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MEASUREMENTS OF RADIATION QUALITY FACTORS USING A RECOMBINATION CHAMBER

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1. INTRODUCTION

The measurement of dose equivalent rates in the presence of neutron radiation is complicated by the necessity to determine the quality factor(QF) of the radiation field. The QF is the absorbed dose of 200 keV photons required to achieve the same biological effect as a unit absorbed dose of the subject field. It has been defined by the International Commission on Radiation Units and Measurements (IC71) as an increasing function of linear energy transfer (LET). LET may, in essence, be operationally defined as the energy deposited by the radiation in a volume comparable to that of biological cells. Thus, energy which is carried out of this volume (e.g., delta rays) would be excluded but otherwise the concept of LET is closely related to the physical quantity dE/dx.

A variety of experimental techniques have been used to determine the quality factor of radiation fields ranging from direct spectrum measurements, which allow one to determine the average quality factor by performing integrations over the energy variable, to direct measurements of LET spectra in the so-called Rossi chamber(Ro68). Presented here is our experience with a recombination chamber. This technique has been described in a CERN report by Sullivan and Baarli (Su63) and summarized in the classic text of Patterson and Thomas (Pa73). In this method, one uses the fact that a high pressure ion chamber operated at a voltage beneath its plateau will measure a greater response to radiation of low LET than to radiation of high LET in fields of equivalent absorbed dose rate. Qualitatively, this results from the fact that the high LET radiation deposits the same energy per gram in dense tracks or clusters so that in the presence of a weak electric field, the migration time of the ions is long enough to allow for them to recombine. For low LET radiation, this columner recombination is much smaller because of the lower density of the ionization(the elections and ions are, on average, further apart).

In the paper by Sullivan and Baarli, the following formula is quoted as describing the response of the chamber as a function of voltage:

$$I=kV^{N} \qquad (1)$$

where I is the normalized current collected by the chamber, K is a constant of proportionality, V is the applied high voltage, and N is a fractional power which can be related to the LET and hence the quality factor of the radiation field. These workers also present a correlation between N and QF based upon measurements in radiation fields of known quality factor. The rest of this note describes a calibration procedure and results obtained in accelerator radiation fields.

2. CALIBRATION PROCEDURE

The Fermilab Safety Section possesses a chamber especially designed for doing recombination measurements[1]. Using this chamber the procedure is to measure its response over its range of operating potentials (up to 1200 volts) by collecting the liberated charge at the anode using a sensitive electrometer such as a Keithley 610C. Equation (1) can be fit to the data using the least squares procedure to obtain a value of N in a field of known QF. For this particular chamber, this was done for several fields of known quality factor. A QF=1 field from a radioactive source (^{60}Co) was used while for a

QF=6.9 field, a ^{238} Pu-Be source was used. The value of 6.9 comes from the work of Höfert and Raffnsøe(Ho80) and, of necessity, includes the contribution of gamma rays emitted from this source. It is thus smaller than the value for just the neutron component. Values of QF intermediate between these two were obtained by mixing the radiation field artificially using sources of various strengths. The quality factor of the mixed field was determined by averaging the absorbed dose rates due to individual sources. In all cases, the gamma and neutron sources were placed very close to each other so that the detector (60 cm away) would be subjected to equivalent field nonuniformities from both sources. This measurement was done in the second floor of a brick house. The effect of scattering from the walls upon both the dose equivalent rate and the flux was calculated using the method of Jenkins (Je80) and found to be negligible for both quantities (less than 4 per cent). The response curves of chamber at different values of quality factor are displayed in Figure 1 along with the fits using Eq(1). These measurements were made in fields having absorbed dose rates ranging between 4.8 and 34 mrad per hour.

In this figure one sees that Eq(1) provides a very good fit to the response curves to first approximation. It does slightly overestimate the response at both the lowest potential(20 volts) and at the nominal saturation potential (1200 volts). Taking the values of N determined in this manner and plotting these as a function of QF in Figure 2, one sees a relationship quite similar to that reported by

Sullivan and Baarli. At this point two different relationships were used to determine a functional relationship $N(QF)$, linear and power law, and these are shown on Figure 2. Both of these are adequate fits to the data for $2 < QF < 7$ which spans the range of quality factor values expected in the neutron fields produced by the Fermilab synchrotrons. For $QF < 2$, the errors are large since the technique requires one to measure a much smaller effect as a function of voltage (small N value). For small values of N, it is better to make comparisons directly to the calibration measurements. Such a situation might be expected in a radiation field which is dominated by muons.

3. MEASUREMENTS IN THE LABYRINTH AT NW3 (1984)

The chamber was used to measure the quality factor in the labyrinth in enclosure NW3 shown in Figure 3. An aluminum target beneath the floor of this labyrinth 30 cm long and of square cross section (15 x 15 cm) was struck by 400 GeV protons in a beam spot having a FWHM of about 1.4 cm (both coordinates) at an intensity of 2 x 10^{11} per spill. The two locations A and B were those at which the recombination chamber was used to make these measuremtents. Response curves similar to the ones shown in Figure 1 was obtained at these two locations, using a tissue equivalent ion chamber (Fermilab chupmunk, using the outputs of the charge digitizer) for normalization. The results are shown on Figure 4. An attempt was made to perform the normalization using the secondary emission monitor in this beamline directly, but the results were much less satisfactory due to short term beam intensity fluctuations not registered by the distant SEM (500 m upstream). The instantaneous absorbed dose rates (during a 15 sec. Energy Saver Spill) were about 0.13 and 0.016 mrad/sec at locations A and B, respectively.

In Figure 4, we see that one can determine the quality factors to reasonable accuracy using this procedure. The result that the quality factor in the first leg of the labyrinth is larger than the value found in the second leg is not surprising since in the first leg, one would expect a more energetic neutron spectrum. The value found in the second leg is consistent with the result of a neutron spectrum measurement by J.Couch, A.Elwyn and W.Freeman (to be reported elsewhere).

4. MEASUREMENTS ABOUT ENCLOSURE EE1(1980)

Prior to the modifications to this enclosure in preparation for the Tevatron Wide Band Neutral Beam Project, EE1 had a very thinly shielded roof which was the source of considerable radiation during 400 GeV operations. Figure 5 shows this enclosure along with two locations of recombination chamber measurements (C and D). The instantaneous absorbed dose rates (during a 1 sec. Main Ring spill) were about 0.8 and 0.04 mrad/sec at locations C and D, respectively.

At the upstream end of the roof of EE1 the absorbed dose rate was predominantly due to neutrons while at the downstream end, the absorbed dose rate was predominantly muons(Co83). The response curves measured for the chamber in these two locations are shown in Figure 6 along with the fits to the data using the procedure described above. The data values were normalized to the P-East SEM at these two locations. As one can see in these results, the quality factor of 4.5 measured at location C is consistent with the general "rule of thumb" value of five predicted by Patterson(Pa71). This agrees with a value of four found in approximately the same location by R.V.Griffith(Gr81) who used a multisphere technique to measure the neutron energy spectrum. At the downstream end (location D), the result is consistent with unity, expected in this field which is known to be predominantly muons. These two measurements could likely have been improved by normalizing to the digital output of a nearby detector, rather than to a somewhat distant SEM.

5. CONCLUSION

It is concluded that the recombination chamber isauseful instrument for determine the approximate quality factor in mixed fields of radiation and may be confidently used in conjunction with other appropriate techniques. The method of measuring the response curve of the chamber appears to be a reasonable approach if one fits the data using Eq(1). One must be careful to choose a method of normalizing the data which is adequate. It appears that the best procedure is to normalize to a nearby detector having a digital readout.

We acknowledge the help of S.Velen, A.Elwyn, and W.Freeman during these measurements.

[1]REM-2 Chamber, ZZUJ "Polon"-Radiation Dosimetry Instrument Division, Bydgoszcz,Poland.

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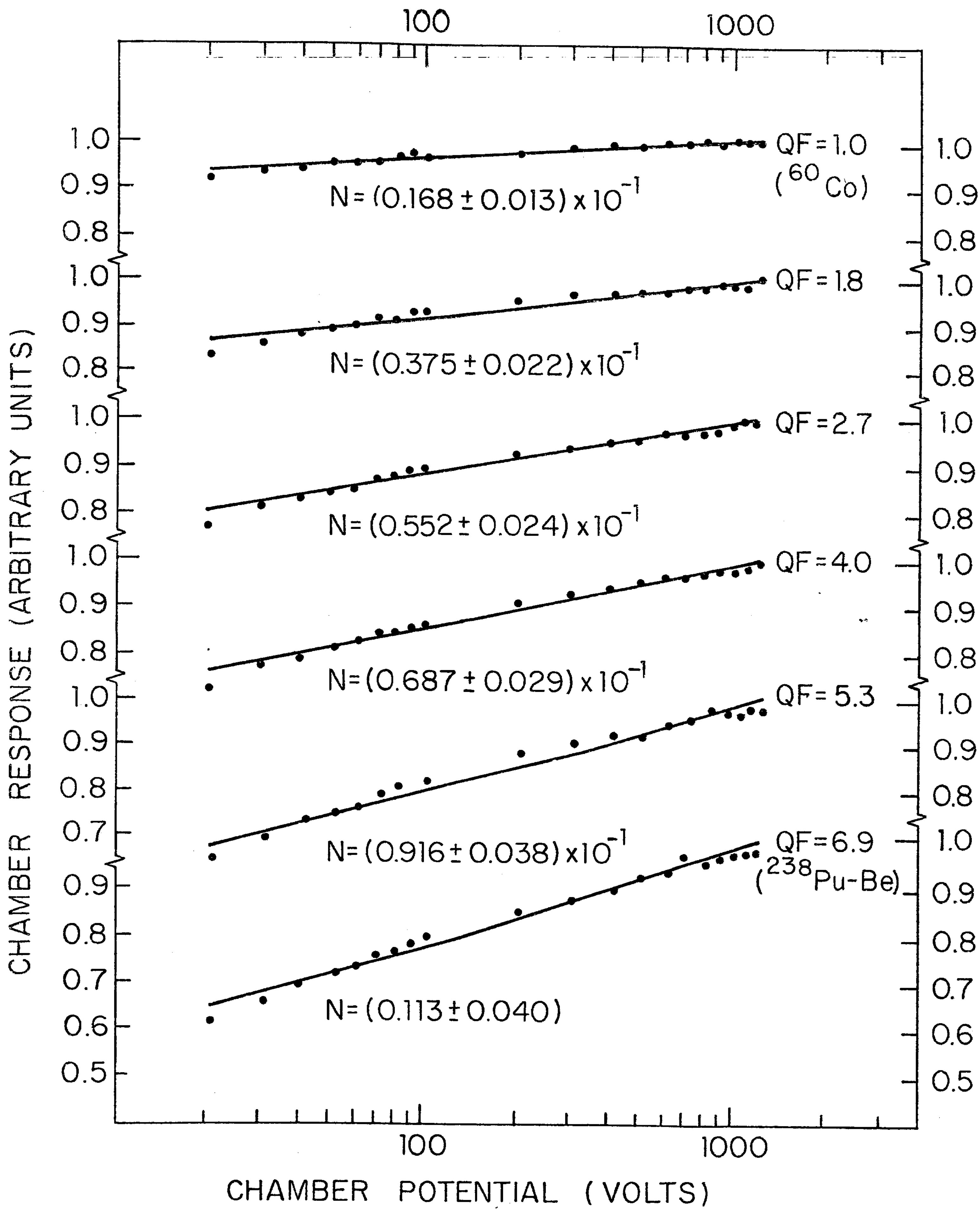
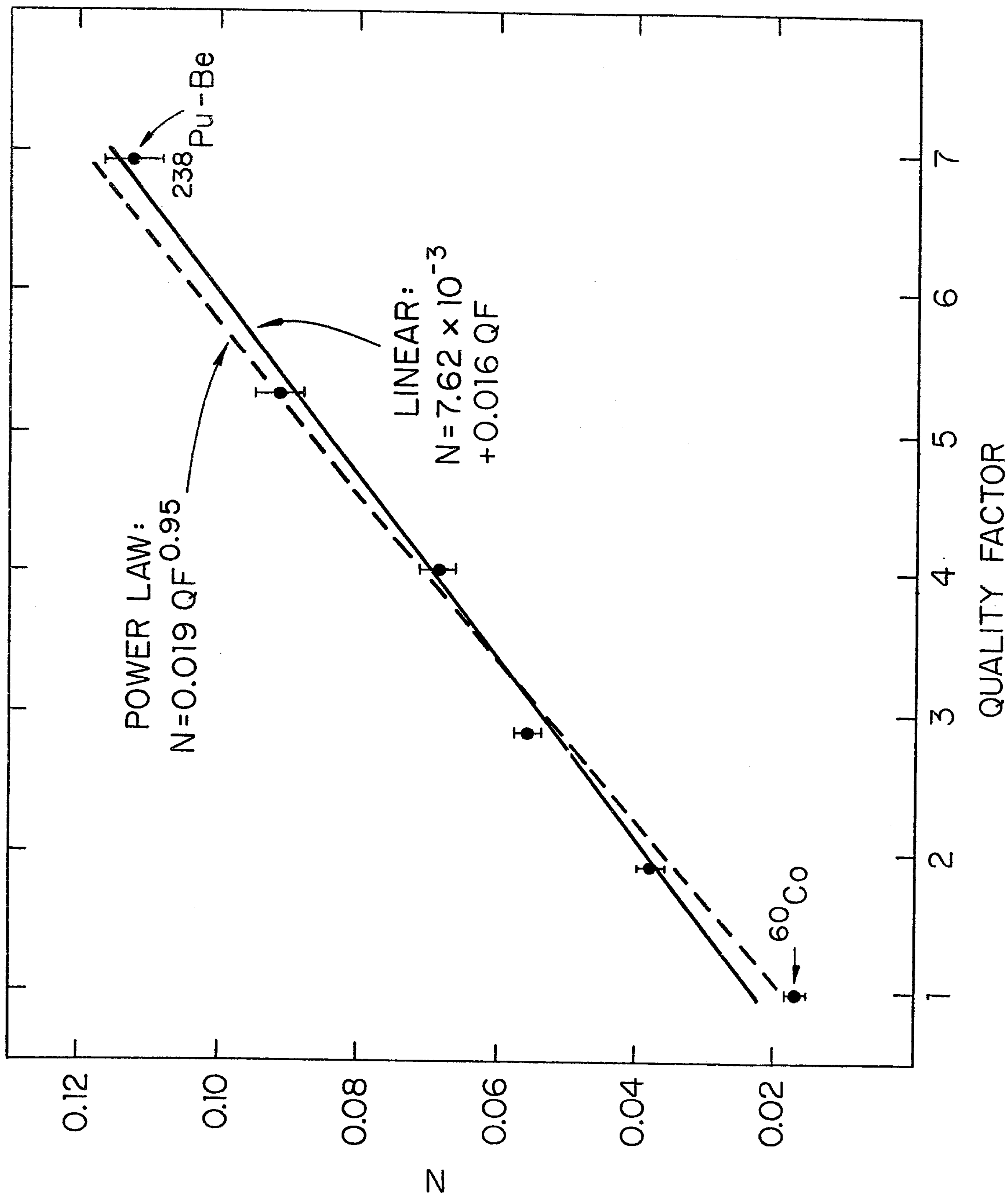

CHAMBER RESPONSE (ARBITRARY UNITS)
CHAMBER POTENTIAL (VOLTS)
100
1000
QF=1.0 (^{60}Co)
N=(0.168±0.013)x10^{-1}
QF=1.8
N=(0.375±0.022)x10^{-1}
QF=2.7
N=(0.552±0.024)x10^{-1}
QF=4.0
N=(0.687±0.029)x10^{-1}
QF=5.3
N=(0.916±0.038)x10^{-1}
QF=6.9 (^{238}Pu-Be)
N=(0.113±0.040)

FIGURE 1



POWER LAW:
N=0.019 QF^0.95
LINEAR:
N=7.62 × 10^-3
+0.016 QF
238Pu-Be
60Co
QUALITY FACTOR
N
0.02
0.04
0.06
0.08
0.10
0.12
1
2
3
4
5
6
7

FIGURE 2

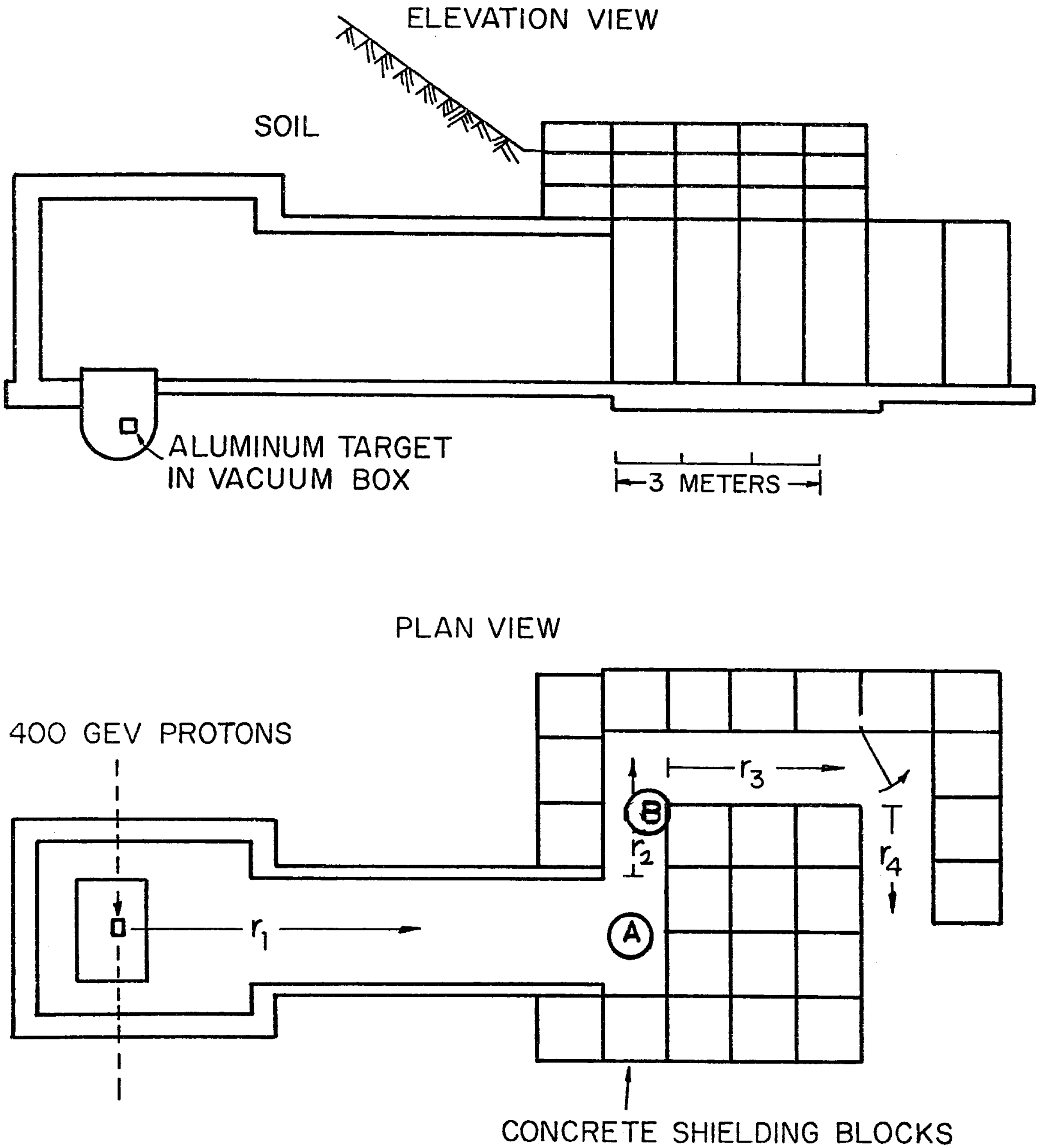

ELEVATION VIEW
SOIL
ALUMINUM TARGET
IN VACUUM BOX
3 METERS
PLAN VIEW
400 GEV PROTONS
r1
r2
r3
r4
A
B
CONCRETE SHIELDING BLOCKS

FIGURE 3

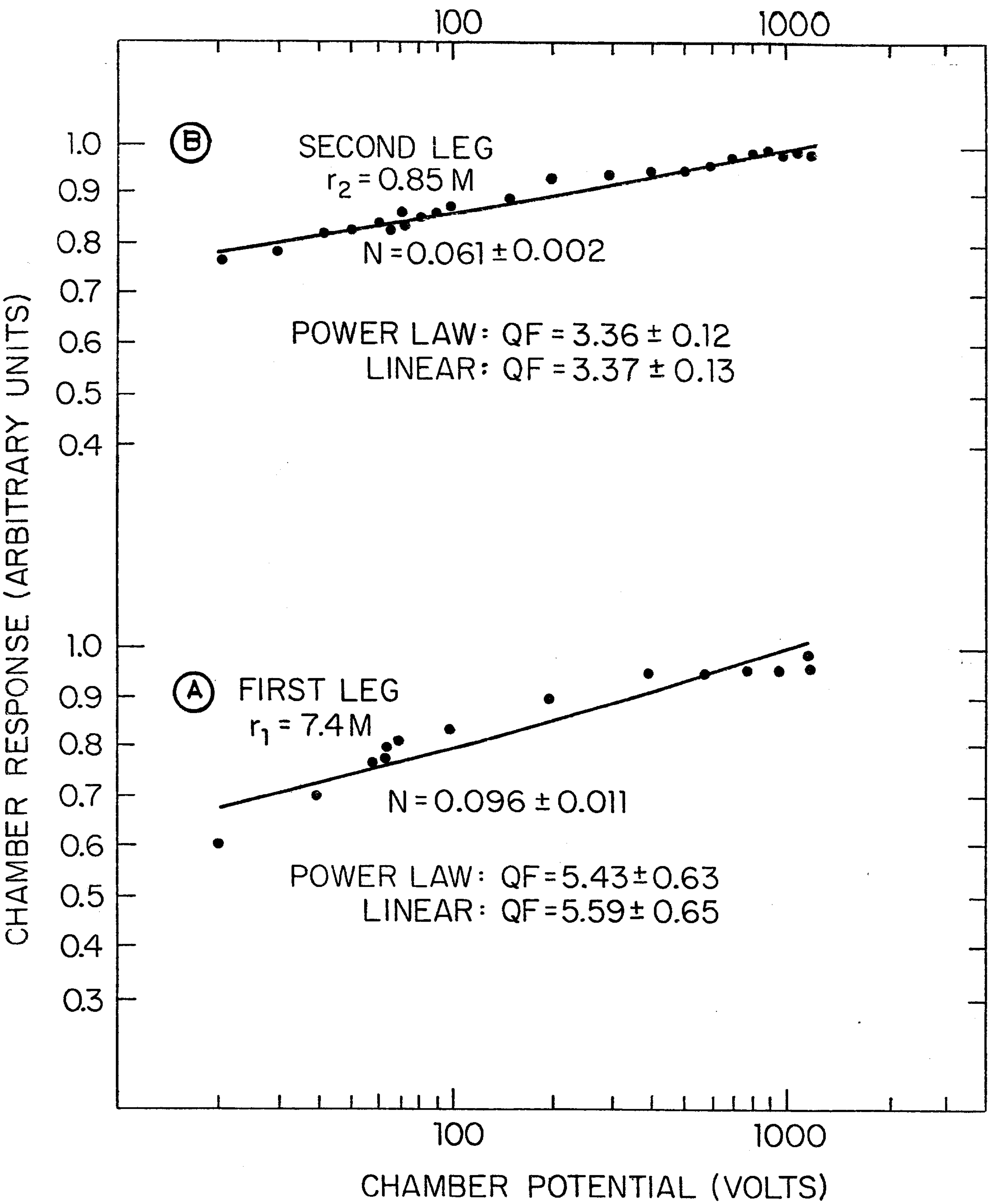

100
1000
1.0
0.9
0.8
0.7
0.6
0.5
0.4
B
SECOND LEG
r2 = 0.85 M
N = 0.061 ± 0.002
POWER LAW: QF = 3.36 ± 0.12
LINEAR: QF = 3.37 ± 0.13
CHAMBER RESPONSE (ARBITRARY UNITS)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
A
FIRST LEG
r1 = 7.4 M
N = 0.096 ± 0.011
POWER LAW: QF = 5.43 ± 0.63
LINEAR: QF = 5.59 ± 0.65
100
1000
CHAMBER POTENTIAL (VOLTS)

FIGURE 4

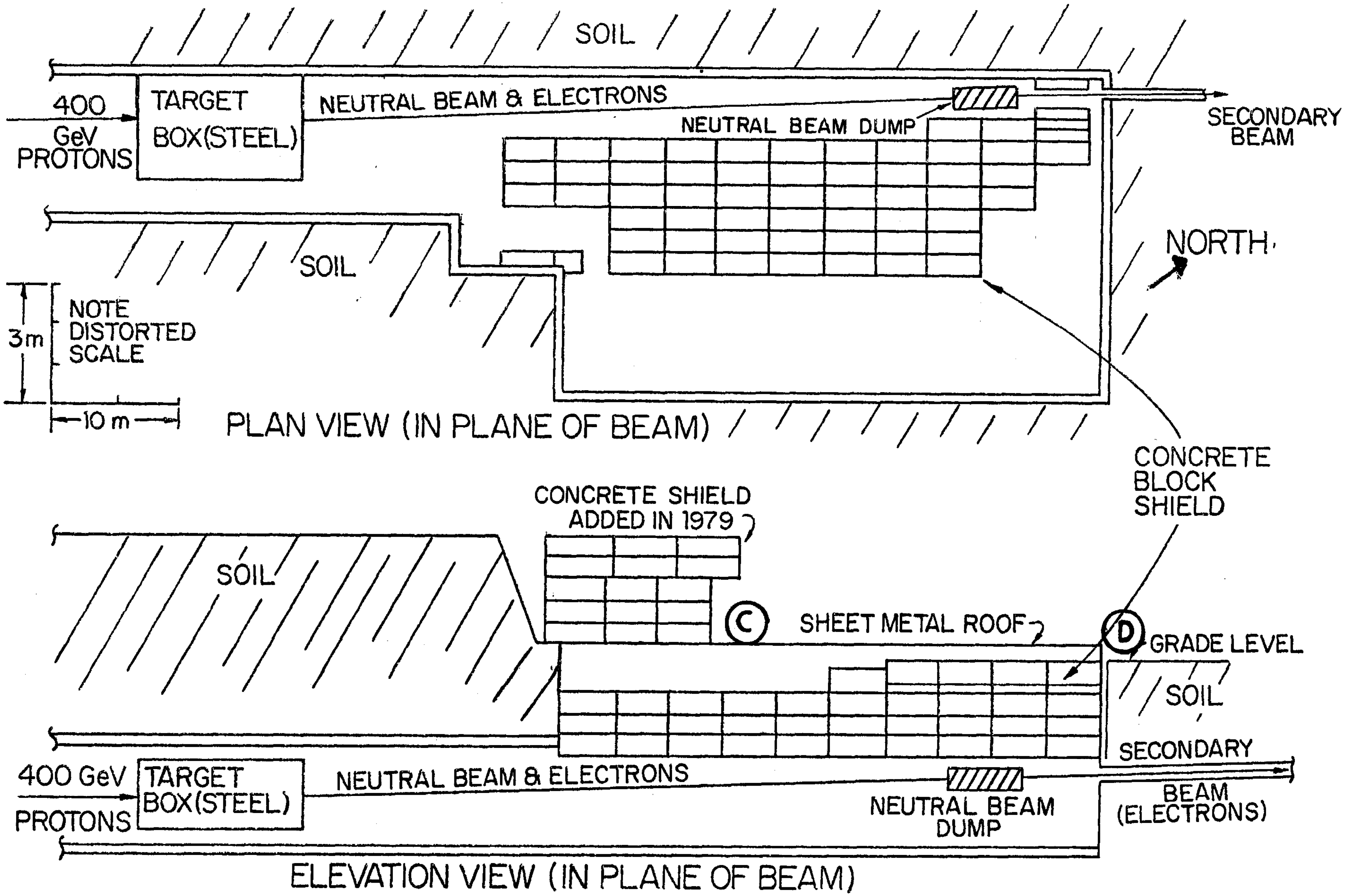
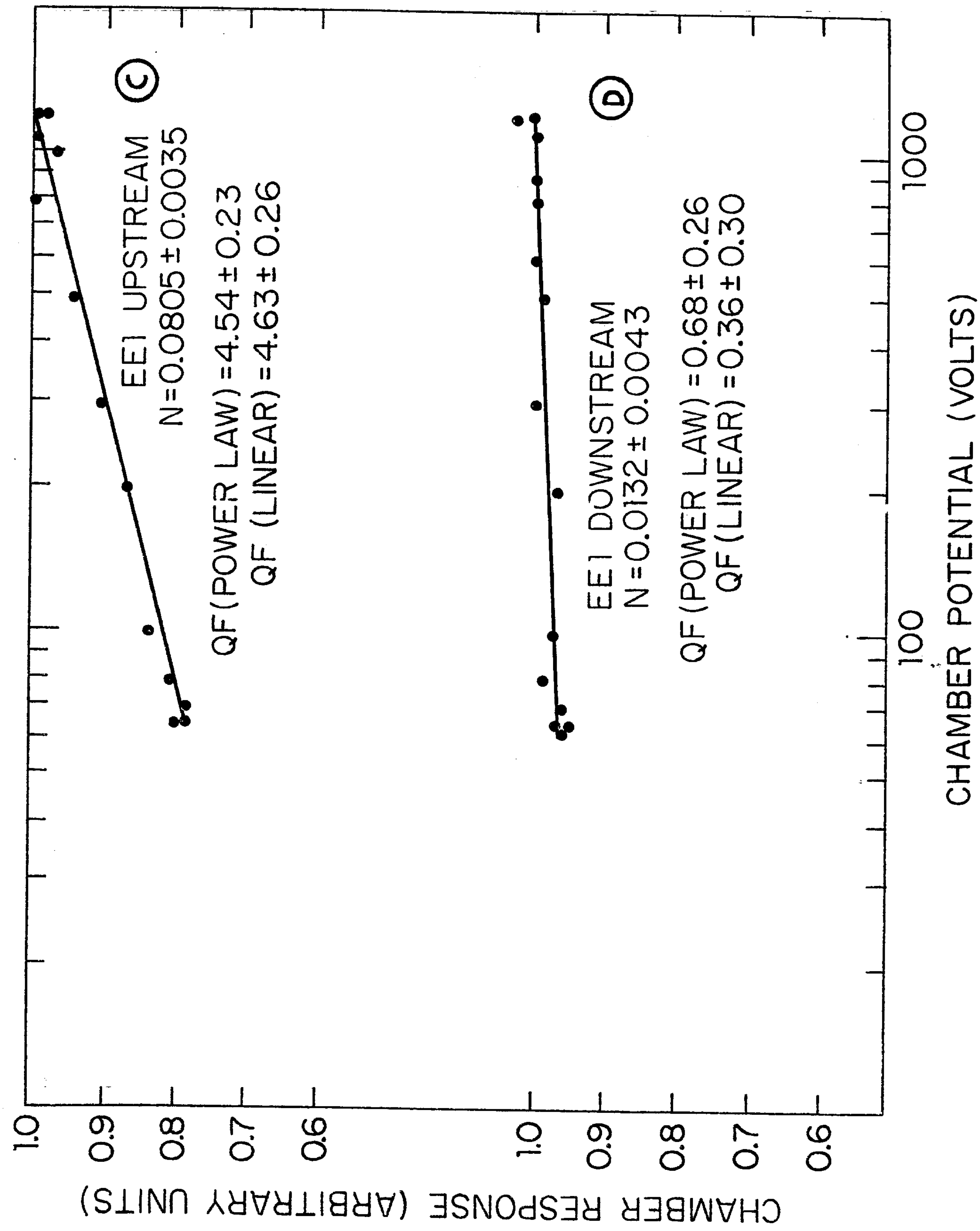

SOIL
400 GeV PROTONS
TARGET BOX(STEEL)
NEUTRAL BEAM & ELECTRONS
NEUTRAL BEAM DUMP
SECONDARY BEAM
NORTH
SOIL
3 m
NOTE DISTORTED SCALE
10 m
PLAN VIEW (IN PLANE OF BEAM)
CONCRETE BLOCK SHIELD
CONCRETE SHIELD ADDED IN 1979
SOIL
C
SHEET METAL ROOF
D
GRADE LEVEL
SOIL
SECONDARY BEAM (ELECTRONS)
400 GeV PROTONS
TARGET BOX(STEEL)
NEUTRAL BEAM & ELECTRONS
NEUTRAL BEAM DUMP
ELEVATION VIEW (IN PLANE OF BEAM)

FIGURE 5



CHAMBER RESPONSE (ARBITRARY UNITS)
CHAMBER POTENTIAL (VOLTS)
100
1000
1.0
0.9
0.8
0.7
0.6
C
EE1 UPSTREAM
N=0.0805±0.0035
QF (POWER LAW)=4.54±0.23
QF (LINEAR)=4.63±0.26
D
EE1 DOWNSTREAM
N=0.0132±0.0043
QF (POWER LAW)=0.68±0.26
QF (LINEAR)=0.36±0.30

FIGURE 6